

# On the sensitivity of transverse flow to the isospin-dependent cross-section and symmetry energy

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We study the transverse flow for systems having various N/Z ratios. We find the transverse flow is sensitive to N/Z ratio and, in fact, increases with N/Z of the system. The relative contribution of symmetry energy and isospin dependence of nucleon-nucleon cross section is also investigated. We find the greater sensitivity of symmetry energy in the lighter systems compared to heavier ones.

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Rapid advances in the technologies to accelerate radioactive ion beams (RIBs) has opened up several new frontiers in nuclear science. In particular, the availability of RIB facilities at Cooler Storage Ring (CSR) (China) [1], the GSI Facility for Antiproton and Ion beam Research (FAIR) [2], RIB facility at Rikagaku Kenyusho (RIKEN) in Japan [3], GANIL in France [4], and the upcoming facility for RIB at Michigan State University [5] provide great opportunity to explore the equation of state and properties of dense neutron-rich matter. This knowledge is important not only for the understanding of the structure of radioactive nuclei, it may also address several critical issues in astrophysics.

The intensive studies by nuclear physics community led to the determination of the equation of state (EOS) of symmetric nuclear matter. In particular, the incompressibility of symmetric nuclear matter at densities greater than normal nuclear matter density has been constrained by the measurements of collective flows [6] in nucleus-nucleus collisions.

The collective transverse in-plane flow has been used extensively over the past three decades to study the properties of hot and dense nuclear matter, i.e., nuclear EOS and in-medium nucleon-nucleon cross section. The study of isospin effects in collective transverse in-plane flow also helps to obtain information about isospin-dependent mean field. The isospin effects in collective transverse flow were first predicted by Pak *et al.* [7]. These isospin effects in collective flow has been explained as the competition among various reaction mechanisms such as nucleon-nucleon collisions, symmetry energy, surface properties of the colliding nuclei and Coulomb force [8]. In Ref. [9, 10] one of us and collaborators predicted the isospin effects in flow and its disappearance for the isobaric pairs. There we found the dominance of Coulomb repulsion over the symmetry energy in isospin effects. In another study of isotopic pairs, two of us and collaborators [11] have studied the effect of symmetry energy on the collective transverse flow of neutron-rich system of  $^{60}\text{Ca}+^{60}\text{Ca}$ . The study revealed the sensitivity of flow to the symmetry energy in the Fermi energy region and shows insensitivity at higher incident energies of 400 and 800 MeV/nucleon. In Ref. [12] Gautam and Sood studied the N/Z dependence of energy of disappearance of flow (energy at which transverse in-plane flow vanishes) throughout the mass range. The study pointed towards the role of symmetry energy in the N/Z dependence of energy of vanishing flow. Motivated by all the previous studies, in the present paper, we aim to see the relative contribution of symmetry energy and isospin dependence of nucleon-nucleon cross section on the collective transverse in-plane flow. The present study is carried out within the framework of isospin-dependent quantum molecular dynamics (IQMD) model

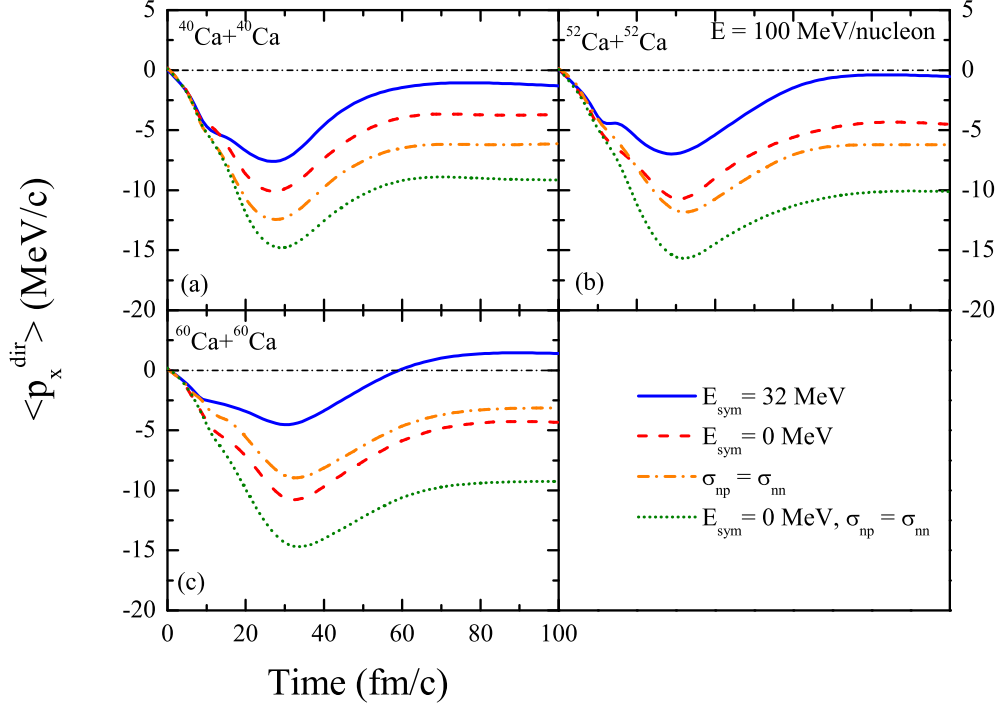


Figure 1: (Color online) The time evolution of  $\langle p_x^{dir} \rangle$  for the reactions of Ca+Ca having  $N/Z = 1.0, 1.6$  and  $2.0$  at  $100$  MeV/nucleon. Lines are explained in the text.

[13].

We simulate the reactions of Ca+Ca and Xe+Xe series having  $N/Z = 1.0, 1.6$  and  $2.0$ . In particular, we simulate the reactions of  $^{40}\text{Ca}+^{40}\text{Ca}$ ,  $^{52}\text{Ca}+^{52}\text{Ca}$ ,  $^{60}\text{Ca}+^{60}\text{Ca}$  and  $^{110}\text{Xe}+^{110}\text{Xe}$ ,  $^{140}\text{Xe}+^{140}\text{Xe}$  and  $^{162}\text{Xe}+^{162}\text{Xe}$  at impact parameter of  $b/b_{\max}=0.2-0.4$ . The incident energy is taken to be  $100$  MeV/nucleon. We use a soft equation of state along with the standard isospin- and energy-dependent cross section reduced by  $20\%$ , i.e.  $\sigma = 0.8 \sigma_{nn}^{free}$ . The reactions are followed till the transverse in-plane flow saturates. It is worth mentioning here that the saturation time varies with the mass of the system. It has been shown in Ref. [14] that the transverse in-plane flow in lighter colliding nuclei saturates earlier compared to heavy colliding nuclei. Saturation time is about  $100$  ( $150$  fm/c) in lighter (heavy) colliding nuclei in the present energy domain. We use the quantity "directed transverse momentum  $\langle p_x^{dir} \rangle$ " to define the nuclear transverse in-plane flow, which is defined as [14]

$$\langle p_x^{dir} \rangle = \frac{1}{A} \sum_{i=1}^A \text{sign}\{y(i)\} p_x(i), \quad (1)$$

where  $y(i)$  and  $p_x(i)$  are, respectively, the rapidity (calculated in the center of mass system)

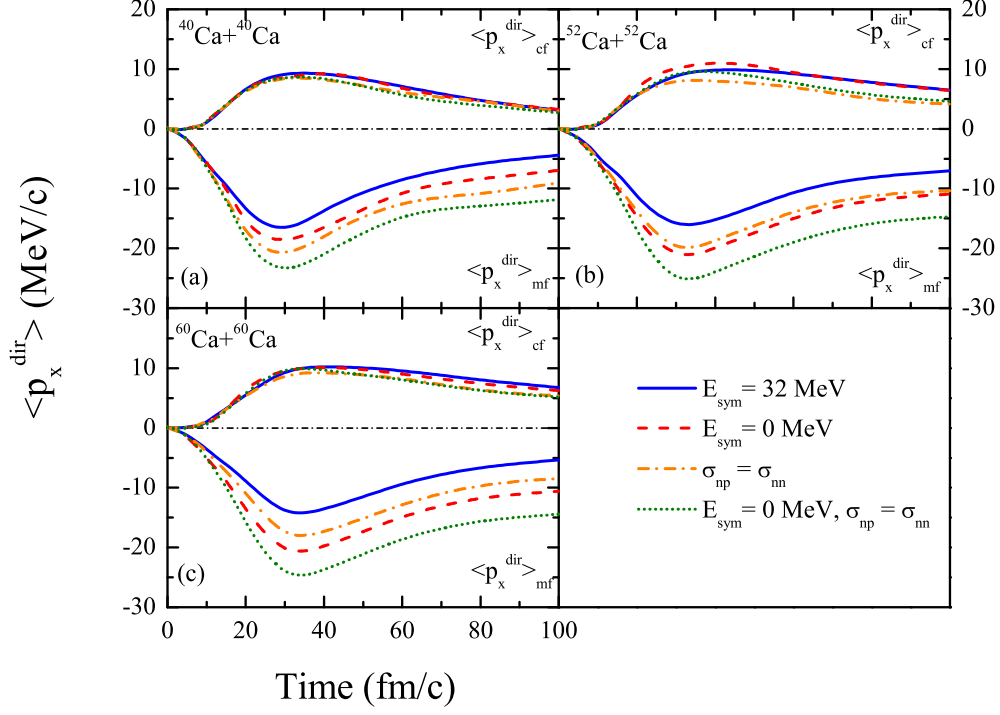


Figure 2: (Color online) The decomposition of  $\langle p_x^{\text{dir}} \rangle$  into  $\langle p_x^{\text{dir}} \rangle_{mf}$  and  $\langle p_x^{\text{dir}} \rangle_{cf}$  for the reactions of Ca+Ca having N/Z = 1.0, 1.6 and 2.0 at 100 MeV/nucleon. Lines have same meaning as in Fig. 1.

and the momentum of the  $i^{\text{th}}$  particle. The rapidity is defined as

$$Y(i) = \frac{1}{2} \ln \frac{\vec{E}(i) + \vec{p}_z(i)}{\vec{E}(i) - \vec{p}_z(i)}, \quad (2)$$

where  $\vec{E}(i)$  and  $\vec{p}_z(i)$  are, respectively, the energy and longitudinal momentum of the  $i^{\text{th}}$  particle. In this definition, all the rapidity bins are taken into account.

In fig. 1, we display the time evolution of  $\langle p_x^{\text{dir}} \rangle$  for the reactions of  $^{40}\text{Ca}+^{40}\text{Ca}$ ,  $^{52}\text{Ca}+^{52}\text{Ca}$  and  $^{60}\text{Ca}+^{60}\text{Ca}$ . We see that at the start of the reaction,  $\langle p_x^{\text{dir}} \rangle$  is negative (due to the dominance of mean-field), reaches a minimum and then increases and saturates at around 80 fm/c. The values of  $\langle p_x^{\text{dir}} \rangle$  is maximum for higher N/Z reaction, i.e.,  $^{60}\text{Ca}+^{60}\text{Ca}$ . Since we are having isotopes of Ca, so Coulomb potential will be same for all the three N/Z reactions. So the isospin effects in the collective flow will be due to the interplay of symmetry energy and isospin-dependent nucleon-nucleon cross section. To

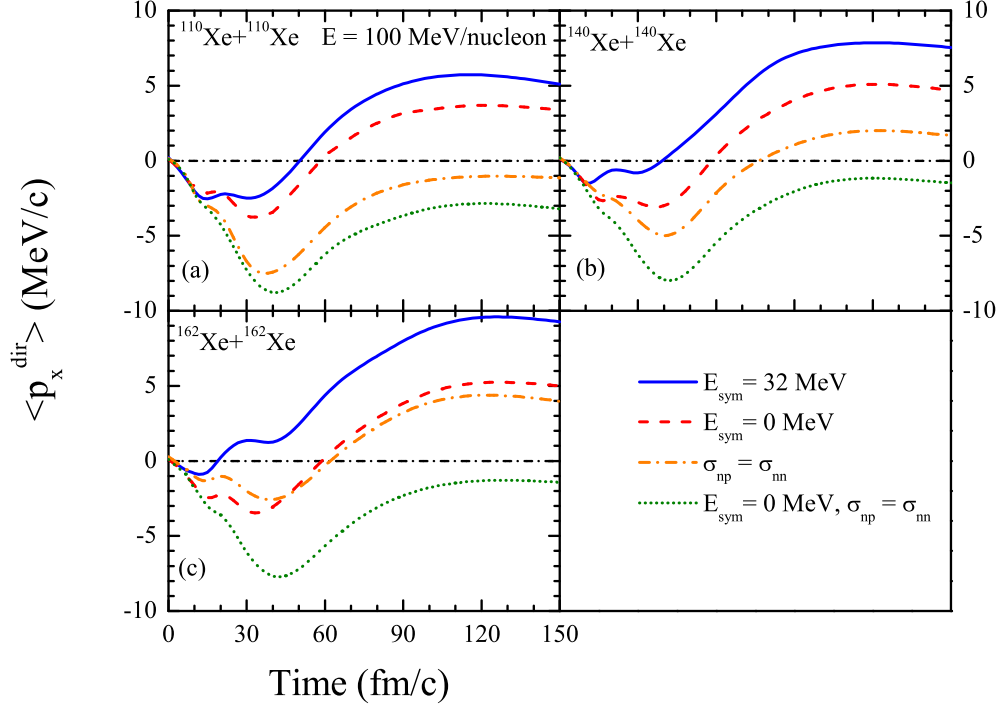


Figure 3: (Color online) Same as Fig. 1 but for Xe+Xe reactions.

see the effect of symmetry energy on the collective transverse in-plane flow, we make the strength of symmetry energy zero. The results are displayed by dashed (red) lines. We see that when we make the strength of symmetry energy zero, the collective transverse in-plane flow decreases in all the three reactions. The decrease in flow is due to the fact that symmetry energy is repulsive in nature and hence leads to positive in-plane flow and so when we make it's strength zero, the flow decreases.

To see the effect of isospin dependence of nucleon-nucleon cross section, we make the cross section isospin independent, i.e.,  $\sigma_{np} = \sigma_{nn}$  and calculate the flow. The results are displayed by dash-dotted lines (orange). We find that the flow decreases when we make the cross section isospin independent. This is because in isospin dependent case, the neutron-proton cross section is three times that of neutron-neutron or proton-proton cross section. When we make the cross section isospin independent the effective magnitude of nucleon-nucleon cross section decreases which leads to less transverse flow. Finally to

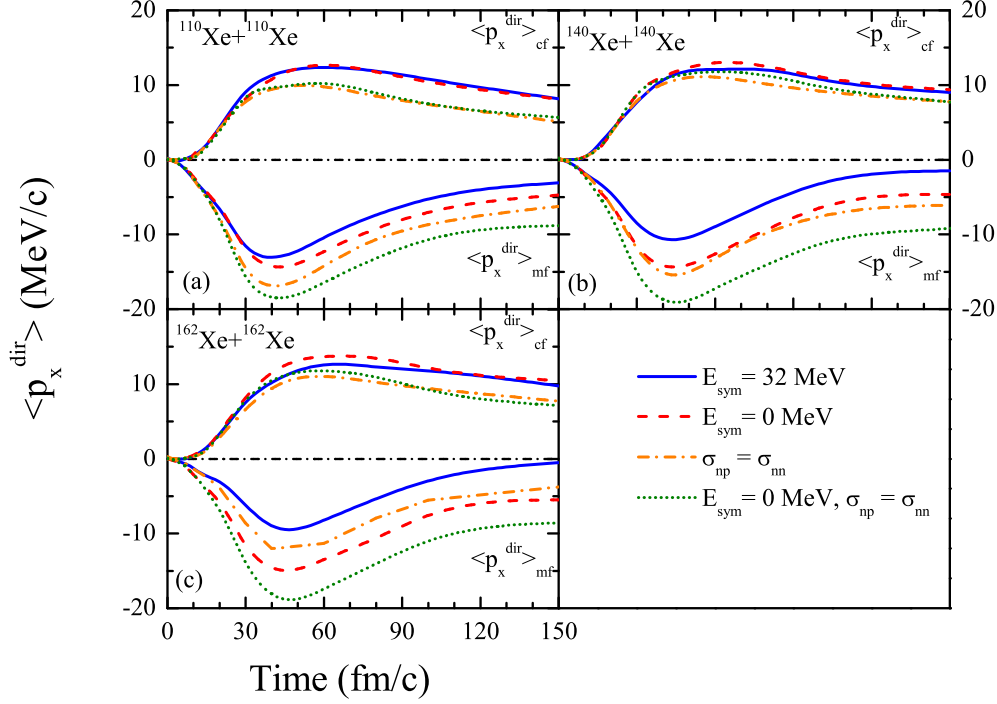


Figure 4: (Color online) Same as Fig. 2 but for Xe+Xe reactions.

see the combined effect of symmetry energy and isospin dependence of cross section, we make both the strength of symmetry energy zero and cross section to be isospin independent, simultaneously. The results are displayed by green lines. We find that the maximum decrease in flow is for  $^{60}\text{Ca} + ^{60}\text{Ca}$  which goes on decreasing as we are moving to symmetric systems.

In fig. 2, we display the mean-field ( $\langle p_x^{\text{dir}} \rangle_{mf}$ ) and collision ( $\langle p_x^{\text{dir}} \rangle_{cf}$ ) contribution to total  $\langle p_x^{\text{dir}} \rangle$  for the reactions of  $^{40}\text{Ca} + ^{40}\text{Ca}$ ,  $^{52}\text{Ca} + ^{52}\text{Ca}$  and  $^{60}\text{Ca} + ^{60}\text{Ca}$ . We see that collision flow remains positive throughout the reaction whereas the flow due to mean field remains negative. We see that when we make the strength of symmetry energy zero, the flow due to mean-field changes and becomes less whereas the collision flow remains almost constant. Similarly the decrease in the flow due to isospin dependent cross section and both symmetry energy and isospin dependent cross section is mainly reflected in mean field flow. We find that the effect of symmetry energy is completely reflected in  $\langle p_x^{\text{dir}} \rangle_{mf}$  (see red and blue lines of  $\langle p_x^{\text{dir}} \rangle_{cf}$ ) whereas the effect of cross section is reflected both in  $\langle p_x^{\text{dir}} \rangle_{mf}$  and  $\langle p_x^{\text{dir}} \rangle_{cf}$  (see blue and orange lines in  $\langle p_x^{\text{dir}} \rangle_{cf}$ ).

In fig. 3, we display the time evolution of  $\langle p_x^{\text{dir}} \rangle$  for the reactions of  $^{110}\text{Xe} + ^{110}\text{Xe}$ ,

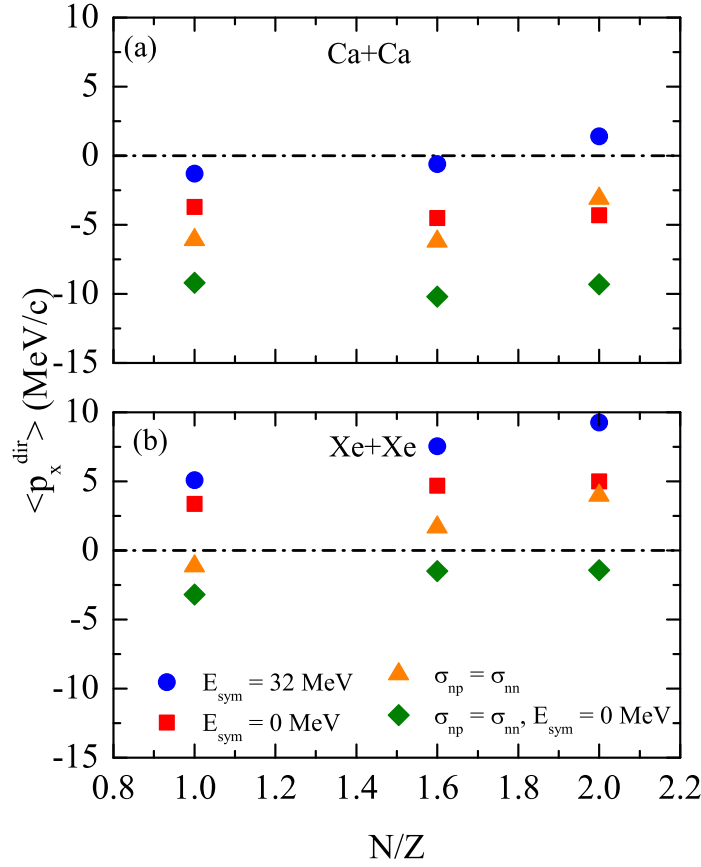


Figure 5: (Color online) The  $N/Z$  dependence of transverse in-plane flow for the reactions of Ca+Ca (upper panel) and Xe+Xe (lower). Various symbols are explained in the text.

$^{140}\text{Xe}+^{140}\text{Xe}$  and  $^{162}\text{Xe}+^{162}\text{Xe}$ . We see that the transverse flow is more than that for the Ca+Ca reactions. To see the role of symmetry energy in heavier systems like Xe+Xe, we again make the strength of symmetry energy zero. The results are displayed by red dashed lines. We find that the flow decreases when we make the strength of symmetry energy zero as for the case of Ca+Ca reactions. Similarly, the flow decreases further when we make the cross section isospin independent. This indicates that the isospin dependence of cross section is dominant than symmetry energy in the isospin effects in transverse flow. The flow decreases further when we simultaneously reduce the strength of symmetry energy zero and make the cross section isospin independent as for the reactions of Ca+Ca.

In fig. 4, we divide the  $\langle p_x^{\text{dir}} \rangle$  into mean field ( $\langle p_x^{\text{dir}} \rangle_{mf}$ ) and collision contribution ( $\langle p_x^{\text{dir}} \rangle_{cf}$ ) for the reactions of Xe+Xe. We find that the effect of symmetry energy is reflected in mean field part  $\langle p_x^{\text{dir}} \rangle_{mf}$  whereas the effect of nucleon-nucleon cross section

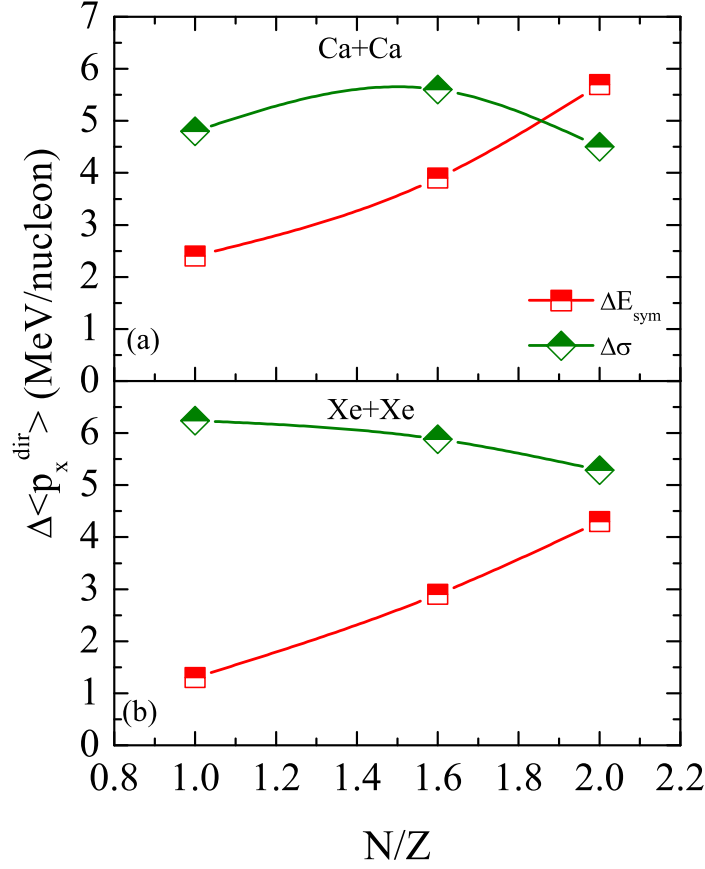


Figure 6: (Color online) The difference in the  $\langle p_x^{\text{dir}} \rangle$  for the reactions of Ca+Ca (upper panel) and Xe+Xe (lower) between calculations with and without symmetry energy and isospin-dependent and independent cross section. Symbols are explained in the text.

is reflected in both  $\langle p_x^{\text{dir}} \rangle_{mf}$  and  $\langle p_x^{\text{dir}} \rangle_{cf}$ .

In fig. 5, we display the  $N/Z$  dependence of  $\langle p_x^{\text{dir}} \rangle$  for the reactions of Ca+Ca (upper panel) and Xe+Xe (lower). Circles and squares represent the calculations with and without symmetry energy, respectively. Triangles and diamonds represent the calculations with isospin independent cross section and both isospin independent cross section and without symmetry energy, respectively. We see that for both the reactions of Ca+Ca as well as for Xe+Xe, the transverse flow increases with  $N/Z$  of the system (circles) due to the enhanced effect of symmetry energy in higher  $N/Z$  systems. The decrease in the flow when we reduce the strength of symmetry energy to zero also increases with  $N/Z$  (see squares). We also see that decrease in flow with isospin independent cross section (triangles) is almost the same for all the three  $N/Z$  reactions for both the systems. This indicates that the role of isospin dependence of cross section is uniform throughout the



N/Z series. This is also predicted in Ref. [12] where the N/Z dependence of energy of vanishing flow is studied.

In fig. 6, we display the change in flow between calculations with and without symmetry energy (red symbols) and isospin-dependent and isospin independent cross section (green symbols). We see that change in the flow increases sharply with N/Z of the system for both Ca+Ca (upper panel) and Xe+Xe (lower) reactions, whereas the change in flow due to isospin dependence of cross section is almost constant with N/Z. Also, the change in flow due to symmetry energy is more in case of Ca+Ca, indicating the greater role of symmetry energy in lighter systems. Thus lighter systems can act as better probes to constrain symmetry energy.

In summary, we have studied the transverse flow for systems having various N/Z ratios. We found the transverse flow is sensitive to N/Z ratio and, in fact, increases with N/Z of the system. The relative contribution of symmetry energy and isospin dependence of nucleon-nucleon cross section is also investigated. We also found the greater sensitivity of symmetry energy in lighter systems as compared to the heavier ones.

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